Maine Department of Transportation

FISH PASSAGE POLICY and DESIGN GUIDE

Prepared by
Maine Department of Transportation

In Cooperation With:
Maine Atlantic Salmon Commission
Maine Department of Environmental Protection
Maine Department of Inland Fisheries and Wildlife
Maine Department of Marine Resources
Maine Land Use Regulation Commission
National Marine Fisheries Service
Natural Resources Conservation Service
U.S. Army Corps of Engineers
U.S. Environmental Protection Agency
U.S. Fish and Wildlife Service

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- Sylvia Michaud

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SUMMARY

The purpose of this document is to establish a policy, process, and design guide with best management practices for fish passage. The document was specifically developed for Maine Department of Transportation (Maine DOT) projects with water-crossing structures. These structures can include pipes or boxes of any type or size, commonly referred to as bridges, struts, culverts, pipes or pipe arches (with or without footings), and could be part of any Maine DOT program. These structures will be referred to as "culverts" or "pipes" in this report. In the past, case-by-case processing of crossings for fish passage (evaluating site through obtaining regulatory approval) could add unexpected time and expense to projects because there were no consistent, established procedures. This document provides a framework, guidance and tools to process crossing projects by balancing a variety of needs at a site.

The primary goal regarding fish passage is to meet regulatory requirements and resource needs, while delivering safe, cost effective, and timely projects. To reach agreement on how best to achieve this goal, representatives from a variety of agencies have met over several months to discuss the issue. The end result is a protocol that encourages balanced decisions on whether fish passage is necessary and, if it is, whether feasible and possible given site conditions and other, potentially limiting factors. Essentially, the document should allow Maine DOT to do the right thing with agency buy in, after weighing all aspects of a proposed project.

INTRODUCTION

Maine's transportation corridors and fisheries resources cross common areas throughout the State, and the Maine DOT is seeking to develop effective ways to build and repair the travel infrastructure while protecting important fisheries resources. Improperly designing, installing or repairing culverts can block spawning runs of migrating fish, as well as the seasonal movement of resident fish species. New structures should be designed and installed so they don't interfere with passage. In addition, any selected method of replacement or repair should allow proper fish passage where appropriate and reasonably possible. Currently, Maine DOT uses the following practices to address a deficient culvert: rehabilitating the existing culvert by inserting a smaller diameter pipe inside, placing a concrete lining at the inverts or throughout the entire length; or replacing the culvert. Rehabilitation allows a culvert to be repaired in place, usually with less streambed disturbance than replacement. Project costs are lower for rehabilitation than for replacement; however, rehabilitated culverts may have more potential to impede fish passage, especially if they did so when they were initially installed.

When examining whether fish passage and associated habitat issues are compatible with new stream crossing structures or improvements to existing structures, Maine DOT must balance the interrelated needs of the site, including regulatory, biologic, hydrologic, structural, and economic. That is, goals for crossings should:

- Maintain or replicate natural stream channel or flow conditions, as appropriate;
- Pass peak flows in accordance with MDOT drainage policy;
- Comply with existing regulations on passing fish;
- Consider potential impacts to rights of way, utilities and traffic;
- Meet appropriate standards and safety requirements;
- Provide reasonable life cycle costs; and,
- Consider the least environmentally damaging solutions.

A multiagency Fish Passage Work Group (the Group) was formed, recognizing that how Maine DOT currently addresses fish passage could be improved to produce better, accelerated and cost effective projects. To identify ways to reach these goals, the Group decided to examine current regulations and policies, current practices in agency coordination, existing standards for fish passage, fish species present and their passage needs, and engineering and other design and construction considerations. After examining these items, representatives of the Group developed recommendations for installing and repairing culverts in a way that:

- Complies to the extent practicable with current state and federal regulations on fish passage [State Natural Resources Protection Act (NRPA) and Land Use Regulation Commission (LURC) guidelines, Federal Endangered Species Act, Magnuson-Stevens Fishery Management Act, and Clean Water Act (CWA)];
- Includes clear protocol for nature and timing of agency coordination;
- Enables the Department to make use of new and developing technologies such as slip lining, plastic pipes, concrete invert lining; and,
- Considers cost and other impacts.

EXISTING REGULATIONS AND RECOMMENDED PRACTICES

Current Regulatory Requirements

Current requirements associated with fish passage and culverts are as follows:

- CWA. Army Corps of Engineers General Permit-39 State of Maine, Item #19(a). "All temporary and permanent crossings of waterbodies shall be suitably culverted, bridged or otherwise designed to withstand and to prevent the restriction of high flows, and to maintain existing low flows, and to not obstruct the movement of aquatic life indigenous to the waterbody beyond the actual duration of construction."

- 38 M.R.S.A. Sections 480 Q. 2.A. and 9. Require fish passage be maintained when existing private or publicly owned culverts are repaired or maintained.

- 12 M.R.S.A., Sections 6121-6123 and 7701-A. May require passage to be constructed at an obstruction (e.g. highway culvert).

- NRPA. Chapter 305. Permit By Rule Standards. Section 11.B.8. Reconstruction or Replacement Projects: "The project will not permanently block any fish passage in any watercourse containing fish. The applicant must improve passage beyond what restriction may exist unless the Department of Inland Fisheries and Wildlife, the Atlantic Salmon Commission, and the Department of Environmental Protection's Division of Environmental Assessment concur that the improvement is not necessary."[1]

- L.U.R.C. Chapter 10. Rules and Regulations. Calls for conditions for fish passage to be maintained.[1]

[1] Work needed on site as part of a fish passage system (e.g. a weir near a pipe outlet) is not considered a project impact and doesn't require a separate permit.

Repair and maintenance of highway culverts must also follow floodplain and flood insurance regulations. The Federal Emergency Management Agency (FEMA) has oversight of all activities that may cause an increase in flooding within a 100-year floodplain. For each crossing project, all appropriate permits shall be obtained and Maine DOT's Best Management Practices for Erosion and Sediment Control (1) shall be used.

Agency Contacts

The Group contacted departments of transportation in Maryland, Minnesota, Michigan, New York, North Carolina, Pennsylvania, Virginia, Washington, British Columbia, Oregon, Alaska, Vermont and Wisconsin, to get ideas from how other states address fish passage. Most of the states contacted assess fish passage project-by-project, coordinating with natural resource agencies (2,3). Some have memoranda of understanding (MOU) with fisheries agencies, as with Washington's MOU among the Fisheries, Wildlife, and Transportation departments, addressing compliance with their Hydraulic Code. Other states have developed guidelines and recommendations, as in North Carolina's "Stream Crossing Guidelines for Anadromous Fish Passage" and New York DOT's recommendations for fish passage that were recently incorporated into their draft highway design manual. None of the transportation departments contacted has a written policy on fish passage.

For environmental coordination of fish passage to be successful, all review parties need sufficient information about whether a resource exists on site and the potential impact of the scope of work on the resource (i.e., whether passage could be blocked by the proposed project). Even small crossings may have locally important fisheries that need to be protected. To assure these concerns are addressed, the Group recommends that Maine DOT continue the current practice of coordinating on fisheries issues with Maine Department of Inland Fisheries and Wildlife (MDIF&W)(4,5), Maine Department of Marine Resources (MDMR)(6), Atlantic Salmon Commission (ASC), U. S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS), as appropriate. To increase project efficiency, the timing and nature of coordination should be better defined.

Existing Standards

In addition to regulatory requirements, the Group recommends that Maine DOT follow the Natural Resources Conservation Service's (NRCS) recently updated National Practice Standard 396 on Fish Passage (7). Following are excerpts from the standard, including general guidance that directly applies to Maine DOT work. In practice, the following should be considered during design of fish passage:

- Actions taken to provide fish passage shall seek to avoid adverse effects to endangered, threatened, and candidate species and their habitats, as well as state species of concern, whenever possible.

- Fish passage measures shall be designed so fish will not suffer excessive energy deficits or undue physical stress when swimming past a fish passage structure or site.

- Fish passage shall be designed so that fish shall not be excessively delayed during passage at the structure or site unless modification or removal of a barrier, such as a tidegate, could result in undesirable effects to other resources.

- Minimum and maximum flows through fish passage structures or sites must be adequate to attract target fish to the structure or site.

- Location and overall design of fish passage structures, or fish passage features, shall accommodate watershed conditions such as variations in stream flow and bedload movement.

- Location and overall design of fish passage structures or features shall accommodate different aquatic species and age classes to the extent possible.

- Location and overall design of fish passage structures or features shall be compatible with local conditions and stream geomorphology.

- Materials selected for constructing fish passage structures will be non-toxic to fish and other aquatic life.

- At stream crossings, flow velocity through culverts should not exceed the abilities of those target species expected to move upstream and downstream of the site.

NRCS also recommends the following considerations:

- Native game and non-game fish species and amphibians as well as endangered, threatened, and candidate, rare and other sensitive species shall be carefully considered when designing and implementing fish passage features.

- If replacement of an in-channel structure will cause degradation or aggradation of the channel upstream, installation of bed controls appropriate for the geomorphic conditions of the site and fish passage needs should be considered (see Stream Channel Stabilization -Code 584 and Grade Stabilization Structure - Code 410).

- Consider potential negative effects of providing passage for invasive or non-native species that may hybridize with, compete with, or spread disease to native fish or other aquatic species above a barrier.

- Consider other aquatic and terrestrial species, including endangered and threatened species that have established habitat in areas where barriers currently exist or in upstream and downstream areas that would be directly affected by the action.

- Consider seasonal variations in headwater and tailwater levels and how these may impact passage hydraulics for the life history stages of the fish for which the structure is being designed.

- Consider the need to design for strategic resting places for target species facing long passages.

- Consider historical structures when planning, prior to installation and during maintenance of fish passage structure. This practice may affect cultural resources.

- Consider the need to balance fish passage with other water management objectives.

- To the extent possible, fish passage structures should be designed to minimize excessive predation on fish entering or exiting the structure.

- Removal of a fish passage barrier should take into consideration effects on wetlands, flooding potential, existing infrastructure and social impacts.

Fish Species Present

The fishery resources of the State of Maine sustain our coastal and inland ecosystems, and provide economic benefits from commercial and sport fishing. Species such as alewife, blueback herring, and American shad provide forage for numerous fish and wildlife species in both inland and coastal habitats (8), and they support commercial fisheries. Other species, such as trout, are sought by anglers and bring revenue into many areas of Maine. All add in some way to the benefits provided by our public fisheries resources and protecting these valuable resources must be one of Maine DOT priorities. Table 1 includes fish species that have been confirmed by the resource agencies participating in the Group as being particularly vulnerable to mortality during their foraging and spawning migrations, and should be considered when designing fish passage.

Table 1. Vulnerable Species

Catadromous Species:	Anadromous Species:	Freshwater Species:
American eel	Rainbow smelt	Rainbow smelt
	Blueback herring	Brook trout
	Alewife	Brown trout
	Atlantic salmon	Rainbow trout
	American shad	Landlocked salmon
	Sea run brook trout	Forage (resident) fish
	Sea run brown trout	White sucker

Site Considerations

First, a resource inventory is conducted at the site and Maine DOT solicits comments from fisheries agencies. Species present, size of fish and seasonal passage needs are determined, using Table 2 as a guide. Even after a resource inventory may indicate that fish passage is warranted, additional features of a site need to be considered. All site factors should be balanced to determine the best course of action.

For example, at a particular site, a hanging pipe may not be realistic to replace. Before a decision is reached, additional questions need to be answered such as: What alternative action is least environmentally damaging? Is cost of any alternative prohibitive, considering short-term costs and life cycle costs? What is the most reasonable alternative considering property ownership? Utility location? Safety? What is best for future streamflow conditions regarding the resources present (fisheries and others) and flood protection? Is there suitable fish habitat upstream of the culvert? In some cases, after it is concluded that fish passage is warranted and appears physically possible, the answers to these questions may alter the final decision on whether passage is practicable and should be provided. Ultimately, a decision to provide fish passage may not be the best decision.

Design Criteria

Introduction

When conditions at a site indicate that fish passage can and should be provided, the appropriate criteria must be used to design effective passage and assure long term stablility at the site. According to MDOT drainage policy, culverts must protect roads against extreme high flow events to avoid blocking traffic and to minimize wash outs and other damage. In addition, at sites with fish habitat, the culverts should not block fish passage. A culvert can block passage in several ways. The most obvious is to create a physical barrier by its configuration or construction (e.g., a hanging culvert). This condition is addressed in the subsequent Design Criteria section on "Gradient." A more subtle form of barrier can be created hydraulically. Although the culvert may appear to form a clear and continuous passage for fish, in fact, the culvert hydraulics (resulting velocity and depth of flow) may prevent passage.

Ideally, culverts should reproduce, as nearly as possible, the hydraulic conditions of the stream. At high flows, this is not an issue, as fish tend not to move upstream during higher flows and depth is more than adequate for fish to wait out the limited duration of higher flows. Low flows are more critical for fish movement. Natural velocities at lower flows ordinarily permit upstream movement. Undersized culverts can constrict flow and increase velocity above the fish swimming capacity. Oversized culverts can reduce flow depths so they are too shallow for fish to navigate. In either case, the culvert may function as a hydraulic barrier to fish movement.

In the discussion to follow, it is useful to distinguish between "high low flow" and "low low flow". Ideally, fish are able to pass during both of these low flow regimes. During "high low flow," depth is presumably adequate, but the higher flow rate may produce a flow velocity that is too fast for fish to swim upstream against. During "low low flow," the flow velocity presumably is adequate for fish to swim upstream against, but the lower flow rate may produce a flow depth too shallow for fish to move through. These low flows must be estimated for each individual stream according to the seasonal variation of flow an accepted percentage of time (50%) that fish must be able to pass the culvert during an identified period of movement.

Ideally, then, to pass fish effectively, culverts must satisfy these objectives:

1) <u>Peak Flow:</u> pass the design flood (typically 50-year) event.
2) <u>Maximum Velocity:</u> not exceed a specified flow velocity at some specified "high low flow" during periods of upstream movement.
3) <u>Minimum Depth:</u> maintain a minimum depth for fish movement at some specified "low low flow."
4) <u>Gradient</u>: Maintain channel elevation between stream bed and pipe at inlet and outlet that fish can easily pass through (no excessive drops).

Design for fish passage through new and replacement ("new") pipes is fundamentally different than for passage through rehabilitated pipes. With new pipes, design is focused on reproducing in the pipe the basic hydraulic geometry of the stream (with Q_2 flow depth as the surrogate for critical geometry). There is the implicit assumption that fish passage criteria 2) and 3) are automatically satisfied if Q_2 flow depth is preserved. With pipe rehabilitation (slip and invert lining), which reduces the size and roughness of the pipe, it is generally not possible to maintain or restore natural hydraulic geometry in the pipe. In this case, criteria 2) and 3) must be addressed directly. The reduced roughness reduces flow depth and/or increases flow velocity. Often, velocity and depth requirements cannot be achieved without additional structural measures (e.g., weirs). In this context, then, the term "rehabilitated culvert" actually connotes a culvert system that will allow fish to pass.

Design Flood

Criterion 1), design flood, is the familiar standard for providing flood protection. In theory, it represents the optimal design that minimizes the expected cost associated with flooding. Damages associated with a design smaller than optimal could be reduced by using a larger culvert. A culvert larger than optimal will cost more than the marginal savings in flood damage. In practice, though, the 50-year event is simply a compromise between underdesign and overdesign. The relationship between the 50-year event and optimal design is largely unknown. Design for criterion 1) is the traditional method of estimating design flow and analyzing culvert hydraulics, as documented in MDOT Highway and Bridge Design Manuals (10, 10a).

Water Velocity

Criterion 2), maximum velocity, is intended to enable the target fish population to swim upstream against the current at critical periods. New and replacement pipes will be sized for consistency with the natural channel bankfull width, with the implicit assumption that such sizing will automatically produce the desired flow velocities and depths.

Various fish species use culverts at different times of the year, and have different velocity and depth requirements for passage. For example, smelt, a weak swimming fish, may be present in the late winter and spring, and require slower velocities than other fish that are present at the same or at different times of year. The same structure may need to sustain a suitable velocity for adult salmonid use in the fall, and to allow low flow passage for juvenile salmon to forage for food during their rearing stage.

Even within species, swimming speeds of fish vary with maturity and size of fish, characteristics of individual fish, and water temperature. There are three categories of swimming speed: cruising, sustained, and burst speed. Cruising speed is the speed a fish can maintain for an extended period of time, sustained speed can be maintained for several minutes and burst speed only for a few seconds. A design to pass fish effectively should be based on sustained speed because it can be used over the relatively short time and distance it takes fish to pass through a pipe. Adults of the weakest swimming fish species found in Maine fisheries, such as smelts, may have maximum sustained speeds around 2.0 feet per second (fps) (8, 9). Therefore, maximum velocity during “high low flow” conditions should be determined for the period that the target fish are moving upstream. It is not necessary to consider maximum flow velocity for downstream movement because fish are moving with the current. Table 2 provides criteria for passage, by species. The table includes sustained swim speed, periods of passage, direction of movement, and size of fish (to determine water depth needed).

Flow velocities vary with depth within the barrel of a pipe, as a function of pipe cross sectional area and surface roughness. A boundary layer of slower moving water develops near the inner pipe surface. Water adjacent to the inner pipe surface (corrugated or smooth) is slower than the flows near the free water surface (or pipe center in case of full pipe flow) and fish will normally seek the lowest water velocity when traversing a culvert (11, 12). Culvert rehabilitation greatly reduces roughness, thus reducing the boundary layer (slow water) thickness to where it may not provide an adequate passage zone. In this case, velocity is nearly uniform across the pipe section and approximately equal to the average velocity as determined by hydraulic equations. When a pipe is sufficiently rough (e.g., deeply corrugated), hydraulic analysis for a specified flow and size may indicate an acceptably thick lower velocity zone adjacent to the pipe surface. If the natural velocity profile in a pipe does not provide an adequate low velocity zone, then alternative designs or actions should be considered (i.e., linings may need to include additional structural measures on site to meet design criteria or it may not be possible to line the pipe).

Designing for maximum velocity requires that target fish species and an appropriate design “high low flow” be specified. Table 2 will be used to establish maximum allowable velocity, corresponding velocity zone depth requirements, and periods of upstream movement by species. Ideally, the design “high low flow” should be based on flow duration statistics for the stream in question. For example, sea-run brook trout move upstream to spawn from September through November. This policy establishes that 50% of that time the fish should have conditions when they can swim upstream. Then, flow duration statistics can be used to determine pipe characteristics such that velocity is less than the allowable maximum 50% of the time.

Flow duration data are not currently available for most Maine streams. In the absence of such data, several actual velocity/discharge measurements ("point-in-time" data) for the critical period can be used for design. If such data are not available, then the monthly average flow(s) as calculated by USGS regression equations (13) should be used, with design for the median estimated flow during the critical period. Point-in-time data should also be augmented with regression calculations. The estimated low flow should also be compared to $Q_{1.1}$. In the event of unacceptable uncertainty in the low flow estimate, design can also be based on $Q_{1.1}$. The actual procedure for calculating this and other conditions necessary for passage are included in the Design Guide.

The Group also examined the use of hydrologic software models, such as FishXing from USFS San Dimas Research Center (www.stream.fs.fed.us/fishxing) as design guidance. Although the model is available, some data needed to run the model are not available for eastern fish species. Therefore, the most feasible approach for Maine DOT is to design passage using the hydrologic: 1) data available; 2) site-specific design criteria; and 3) in-house expertise.

Water Depth

Criterion 3), minimum depth, is intended to assure adequate water depth during periods of simultaneous "low low flow" and fish movement. As already noted for water velocity considerations, new and replacement pipes will be sized for consistency with the natural channel bankfull width, with the implicit assumption that such sizing will automatically produce the desired flow velocities and depths.

For culvert rehabilitation, the design depth should be based on the target species present and either the corresponding critical depth (1.5 x the body thickness) (14) for that species during the period of significant movement or the documented prevailing depths during periods of known movement. Ideally, the design "low low flow" should be based on flow duration statistics for the stream in question. For example, if August is the month of lowest monthly average flow and is a month of known fish movement, the culvert might be designed to maintain a species- and size-dependent depth at a flow that is not exceeded some specified percentage of the time. In the absence of flow duration data, actual depth measurements for the critical month(s) should be used, in which case the connection between design depth and species is not maintained. If such data are not available, the monthly average flow(s) as calculated by USGS regression equations (13) can be used. The estimated low flow should also be compared to $Q_{1.1}$. In the event of unacceptable uncertainty in the low flow estimate, design can also be based on $Q_{1.1}$. Regardless of the flow/depth data source, the designer should be sure that the design depths actually prevail in the stream. Otherwise, the ability to maintain design depth in the culvert may not be practical, or meaningful.

Information we received from other regions confirms that sizing and orientation of culverts are regionally specific because of different geographic and hydrologic conditions at water crossings. For example, Washington State requires that a culvert be 1.2 times the bankfull (roughly $Q_{1.1}$) width plus 2 feet at the flow line. This design is inappropriate for Maine because it would create inadequate depths for resident fish passage in many instances. We endorse USFWS (15) recommendations to design for varying suitable flow conditions to match existing stream depth at the pipe location during key periods of use. We also recommend that any replacement pipe should approximately match the width of the existing bankfull stream channel at Q_2, to maintain adequate water depth.

Gradient

In addition to a suitable combination of water velocity and depth, fish need criterion 4), a suitable gradient to enter and exit a crossing structure (3,8,11,12). A drop at a culvert outlet is one of the most critical conditions that can block passage. Culverts should be installed at the proper elevation to avoid perched outlets that fish cannot access. This agrees with current Maine DOT practices that pipes should be embedded and allowed to fill in to maintain a continuous, natural gradient. In some instances, weirs or a check dam can be placed downstream from an existing culvert to raise the tailwater elevation enough to reduce or eliminate a drop and allow passage, as long as passage at the check dam is maintained.

Summary of Maine Criteria

Design for fish passage through new and rehabilitated culverts is fundamentally different. Each site where passage is desired will need biologic and hydraulic analyses, so case by case project review is the best way to address passage issues and design. Pipes will be designed for appropriate flow depth and velocity, either implicitly (new or replacement) or explicitly (rehabilitation). The Best Management Practices for Fish Passage (Appendix B) will be used as design guidance. If a particular site cannot physically meet these criteria or if cost is prohibitive, design criteria for passage may be revised or suspended.

Considering all the data available and sound current practices, the following conditions should be our goals when fish passage is needed. These goals are in addition to the requirement that culverts pass the design peak flows.

Goals for New or Replacement Culvert

- Establish and verify instream work window.
- Eliminate hanging outlets where practicable.
- Install new structures with inverts below streambed elevation. Pipes less than 1200 mm (48 in) in diameter should be embedded 150 mm (6 in); and pipes 1200 mm or more in diameter embedded 300 mm (12 in) into the stream bottom. Embedded pipes should be allowed to fill with natural substrate (6).
- Structures should allow existing stream bed characteristics to be naturally maintained, as much as practicable.
- Do not exceed the existing natural gradient; avoid drops inaccessible to fish.
- Size and place structures to simulate natural stream hydraulic geometry (including bankful width). For single pipes, match flow depth to natural stream depth at bankfull (Q_2) conditions.
- For multiple pipes at the same location, install as for single pipe to allow fish passage during low flow periods of regular movement; size and place additional pipe to collectively pass the design peak flows (4, 6, 10). Multi-pipe installations are prone to unintended consequences and should only be designed by experienced hydraulic engineers.

- Calculate flow depth during species-specific periods of movement for the pipe design at appropriate period-specific low flows.

Goals for Rehabilitated Culvert

- Establish and verify instream work window.
- Eliminate hanging outlets where practicable.
- Preserve minimum flow depth during critical periods of species-specific movement.
- Do not exceed maximum flow velocity during periods of species-specific upstream movement.

The Design Guide's Best Management Practices for passing fish (Appendix B) will be used where pipes are being replaced (if replacement pipes cannot be lowered to proper grade) or rehabilitated.

Process

Project Coordination

Maine DOT's Bridge Management Section initially field-reviews bridge project sites to establish a six year plan. A biologist participating in the review will document, at that time, what is known about projects and site conditions (including whether there is a defined stream channel, fish and habitat). The preliminary site inventory form and instructions in Appendix A will be used starting at this initial review and data collected will be entered in a data base. Next, the data collected will be sent to the agencies with requests for work windows, passage needs and other habitat issues. Information received following those requests will be permanently put into each project's file to be used during design and construction.

For the Bureaus of Maintenance and Operations and Project Development (teamed) projects, a Maine DOT biologist or other appropriate staff will also do a preliminary site inventory and record information in the data base as early as possible after projects are initiated. The DOT will then forward data and request agency comments, placing responses in each project's files.

Figure 1 outlines processing steps, beginning with project initiation and continuing through project construction. Proposed scope of work is the first data known for each project. After initial site information is collected, either fish passage is requested for the species of concern, or passage is determined not necessary. When determining needs at site, all other site conditions are defined, including potential environmental effects and overall practicability (cost, property ownership, utilities, safety, etc.). If passage appears practicable after all factors have been reviewed, a hydrologic assessment will be done to determine whether passage can be properly designed. The proposed design is submitted to the appropriate regulatory agencies and a response is sent to Maine DOT. Lastly, agencies agree on what should be done and construction can proceed.

During placement of a weir or other passage measure, a Maine DOT or other environmental representative will be present on the project to assist with placement by offering resource considerations and site-specific adjustments when necessary.

Project Monitoring and Evaluation

Projects completed under the terms of this document will be monitored and evaluated. A monitoring plan will be developed to evaluate effectiveness, including use by fish and hydraulic performance, and site stability, for a specified period after the project has been constructed. Results of all sites monitored for any given year will be documented in writing and by photographs/videos. These results will be presented to the Interagency (or similar) group and kept on file at Maine DOT so they are available upon request.

A technical working group will be established to evaluate engineering practices associated with fish passage. This group will assure that examples of successful practices are added to the BMP section of this report as appropriate so they can be used to design future similar projects. Measures that are unsuccessful will be examined for the cause of failure and either eliminated as an alternative (with documentation) or modified in a way that makes them effective.

RECOMMENDATIONS

To reach our goal of compliant, constructible, on time projects, we offer the following additional recommendations for follow up actions.

- Policy and Guidelines. This report is a comprehensive, living document on fish passage, and will be kept current to address future needs concerning resources or crossings. Major proposed changes will be sent to appropriate agencies for review before being incorporated into the document.

- Fish Passage Design Guide and BMPs. The Design Guide and Best Management Practices established in this document will also be included in appropriate Department manuals.

- Monitoring Plan. Maine DOT, in coordination with appropriate resource agencies, will develop a monitoring plan to be used on all constructed sites with special fish passage features.

- Data Base. A data base will be developed from the Preliminary Site Inventory Form and, as data is collected, the information will be recorded in the data base and linked to related, existing Maine DOT data bases. This will help to identify and expedite future repair or replacement of culverts.

- Inspection Protocol. Maine DOT will coordinate culvert inspections to identify specific needs early so culverts can be assessed and replaced or repaired before they fail. This will also allow ample time for agency coordination.

- In-house Training. Potential users of the Fish Passage policy, guidelines, design guide and BMPs will be offered training on how to use the information in this report. These users include Maine DOT staff who coordinate environmental aspects, design and construct crossing projects.

- Effective Date. This document will be officially announced at appropriate state, federal, local or other appropriate forums, beginning in the spring of 2002.

Table 2. Maine Fish Species: Times of Impact and Related Data.(1)

Months				Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov			
Stage/species	**Body Length (inches)**	**Body Thickness (inches) (% body length)**	**Direction**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**Sustained Swim Speed (feet per second)**	**Basis of Swim Speed**
adult smelt-landlocked	5.5 - 9.7*	0.9 - 1.5 (16%)#	U	S	S	S	S	S	S	S	S													1.8 - 3.2	L
adult smelt-anadromous**	5.5 - 9.7*	0.9 - 1.5 (16%) #	U			S	S	S	S	S														1.8 - 3.2	L
adult smelt-anadromous**	5.5 - 9.7*	0.9 - 1.5 (16%) #	D			F	F	F	F	F														1.8 - 3.2	L
juvenile smelt-anadromous**	0.74 - 5.5	0.1 - 0.9 (16%) #	D			F	F	F	F	F														0.2 - 0.4	L
juvenile eel (glass & elvers)	2.3 - 5*	1/8 - 1/2	U				S	S	S	S	S	S	S											0.8 - 2.6	L
adult eel	7.8 - 26***	1 - 2 #	D														F	F	F	F	F			5.2 - 9.1	L
adult alewife	2.6 - 9.4*+	0.8 - 2.8 (30%) +	U							S	S	S	S											3 - 5	Pb
adult alewife	2.6 - 9.4*+	0.8 - 2.8 (30%) +	D								F	F	F	F										3 - 5	Pb
juvenile alewife	1.7-4.5*	0.5 - 1.4 (30%) +	D												F	F	F	F	F	F	F			0.6 - 1.0	L
adult shad	12-17*	2 - 3 (18%) +	U								S	S	S	S										2.3-7.2	Pb
adult shad	12-17*	2 - 3 (18%) +	D								F	F	F	F										2.3-7.2	Pb
juvenile shad	3*	0.6 (18%) +	D												F	F	F	F	F	F	F			1.0 - 1.8	L/Pb
adult blueback herring	9.4 +	2.2 (23%)	U								S	S	S	S										3 - 5	Pb
adult blueback herring	9.4 +	2.2 (23%)	D								F	F	F	F										3 - 5	Pb
juvenile blueback herring	1.4 - 2.8*	0.3 - 0.7 (23%)	D												F	F	F	F	F	F	F	F		0.4 - 0.8	L
adult salmon(searun/landlock)	15 - 36*	3 - 7.2 (20%)	U															S	S	S	S	S	S	5.0 - 8.8	L
juvenile salmon	4.5 - 6.8*	1 - 1.4 (20%)	Both					F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	1.6 - 2.6	L
smolt salmon	7.8 - 15*	1.4- 5 (20%)	D					F	F	F	F	F	F											2.5 - 4.4	L
adult white sucker	4 - 14 +#	0.7 - 2.6 (18%)	U					S	S	S	S													1.2 - 2.1	L
brown trout	6-16*+	1.6 - 3 (18%)+	Both					F	F	F	F	F	F	F	F	F	F	S	S	S	S	S	S	2.3-7.5	Pb
brook trout	6-16#	1.5 - 4 (25%)	Both					F	F	F	F	F	F	F	F	F	F	S	S	S	S	S	S	2.0 - 3.5	L
sea-run brown trout	9-16*+	1.6 - 3 (18%)+	U															S	S	S	S	S	S	2.3-7.1	L
sea-run brook trout	6-12#	1.5 - 4 (25%)	U															S	S	S	S	S	S	2.0 - 3.5	L
rainbow trout	6-18 +*	1 - 3 (17%)	Both			S	S	S	S	S	S													2.0 - 3.5	L/P+
resident fish movement	3 - 10#	Varies	Both				F	F	F	F	F	S	S	S	S	S	S	F	F	F	F	F	F	1.0 - 1.8	L

Abbreviations/comments

(1) Jan, Dec no feeding or spawning needs noted; Months of passage may vary over different regions of Maine; Not intended as denoting construction work windows

Body thickness x 1.5= water depth needed for passage

Swim speeds - based on smallest size measurement
Sustained speed = 4 to 7 body lengths per second

* USFWS HIS Models

******For culverts just above head-tide; tidal culverts would impact over longer period

******* USFWS HIS New Brunswick

D=downstream migration
U=upstream migration

F=Feeding, foraging, refugia (any instream movement)
S=Spawning or spawning migration

1= first half of month
2= second half of month

P =Published Speeds. b (Bell); + (Fishbase)
L = Body Length Formula

\# Anecdotal or observed ranges
\+ Sizes from: www.fishbase.com

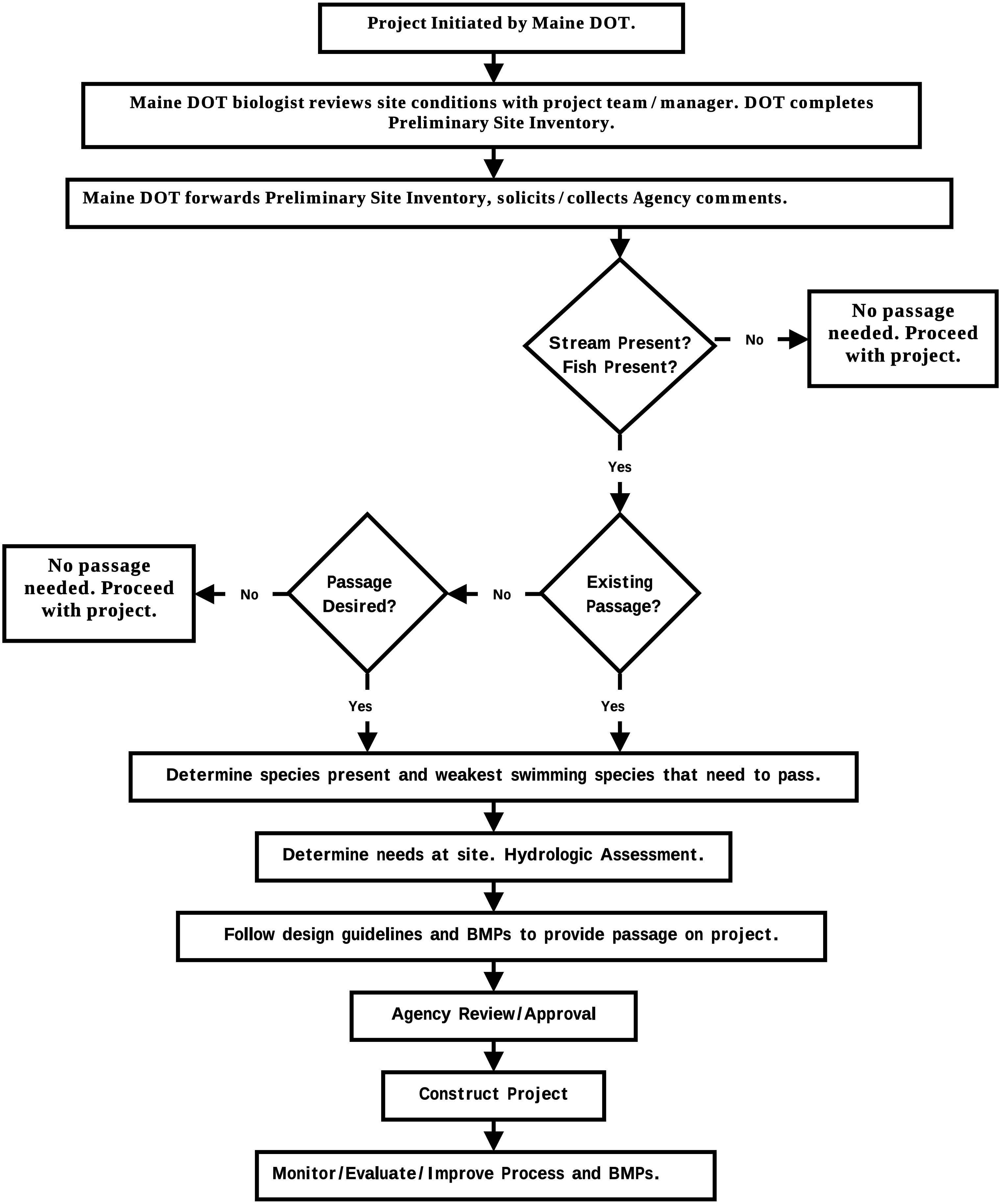

Figure 1. Steps in processing Fish Passage.

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APPENDIX A. Preliminary Site Inventory Form and Instructions

Part I. Preliminary Site Inventory. (Use back of form or additional pages as necessary.)
Purpose: This site inventory should be completed as early as possible for projects with crossing structures, and used to help evaluate alternatives for final scope of work at a site (rehabilitation or replacement). The completed form will provide a portion of the information needed to determine appropriate action and is part of the Maine DOT Fish Passage Policy and Guidelines.

Please complete sections I. through IV. For help, see Selected Instructions by Section below.

I. General	Date: Reviewer: Agency/Phone:		
Town/Route/Road Name:		PIN/Div/Br. #:	
Waterbody Name:		Watershed:	
Map Location:		Latitude\Longitude: GPS U.S.G.S. map	
Collector Route Code:	Route Mileage:	Element ID:	
II. Stream\Fisheries Observations			
Cover type: forested shrub grassy Describe:			
% Gradient Upstream: 0-1 1-4 >4 % Gradient Downstream: 0-1 1-4 >4		% Shading Upstream: Downstream:	
Existing structures or barriers: Upstream Downstream Describe:			Estimated Stream Velocity:
Culvert width: Matches stream Narrower than stream Wider than stream			
Fish present: Yes No Unsure		Fish Observed: Upstream Downstream	
Fish species/size/age class:			
Existing structure passable?: Yes No Unsure If no, why? Describe:			
III. Culvert Observations/measurements			
Structure type/shape: Corrugated: Yes No Depth of corrugations: Spacing of corrugations:			
Structure Height/Diameter: Width: Length:		Orientation:	
Embedded invert: Yes No Approx. depth below substrate at Inlet: at Outlet:			
Alignment with stream: Horizontal: Good Fair (Upstream or Downstream) Poor Vertical: Flatter Same Steeper			

Water depth in structure: at Inlet: At Outlet: High water marks:		
Inlet: Describe: Apron: Yes No Type:		
Outlet: Physical drop Cascade If drop, difference from invert to streambed:	Apron: Yes No Type:	Age of structure: years
Average water depth in stream:	Size of area draining into pipe:	
IV. Other	Photos: Digital (preferred) Other	Sketch: On back On additional page
Other observations: Back Added page(s)	Rare, Threatened, Endangered Species present? Yes No Unknown Describe:	
Need further review? Yes No Describe:		

Part II. Instructions for completing Preliminary Site Inventory

Selected Instructions by Section:

I. General

Watershed: Name of watershed basin that contains the waterbody from DeLorme Maine Atlas (DeLorme) or U.S.G.S. Map.

Map Location: 7.5 minute USGS topographic map name or coordinates from DeLorme. For DeLorme, use Map Number and alphanumeric locator (e.g.: Davis Brook, #34, B - 1).

Latitude and longitude: Enter coordinates and indicate if GPS or U.S.G.S. map used.

Collector Route Code, Route Mileage, Element ID: These are identifiers from the M&O Asset Inventory Data Base that can be used for cross-referencing.

II. Stream and Fisheries observations

Cover type: Circle one or more, as appropriate. Add brief description of cover/habitat in area of structure. Include human development in adjacent area, evident disturbances, special concerns.

Gradient: Circle as appropriate. Look at channel up and downstream of crossing to make determination.As a general rule: **0-1%** slope area characterized by no to slow moving current; **1 to 4%** gradient usually show a riffle\pool overall flow pattern, with moderately fast moving water spaced between pools and no to slight current; **> 4%** characterized by 'pool and drop' overall flow pattern, with steep drops (such as rapids and waterfalls) spaced between pools of significantly slower flow.

Shading: Approximate percent cover in areas near inlet and outlet. Observe canopy over water up- and downstream of crossing. (Vegetation cover is important in moderating stream temperatures and providing basis for food webs within waterbody.)

Estimated Stream Velocity: Use flow meter or estimate travel time over known distance.

Culvert width: Note how width of crossing structure 'fits' stream channel width near inlet and circle appropriate response.

Fish species/size/age class: If possible, note. If not possible, record numbers, body shape or any other apparent characteristics of observed fish.

<u>III. Culvert observations and measurements:</u>
Structure type: Fill in type of structure, including metal, concrete, pipe, box, arch, etc.

Orientation: For example, N/S or E/W

Embedded invert: Is invert of structure below substrate surface? Circle appropriate response. If structure below streambed elevation, estimate depth of invert below substrate at inlet and outlet.

Alignment with stream: Is existing structure aligned with channel? Look at local setting upstream and downstream before completing.

Horizontal:

- <u>Good</u>: approximates general course of stream.
- <u>Fair</u>: structure not well aligned with either inlet OR outlet of waterway. Indicate upstream or downstream.
- <u>Poor</u>: structure distinctly out of line with channel.

Water depth in pipe: Measure any high water mark above existing water level.

Inlet: One or two words describing inlet. Include whether inlet is projecting, has a headwall, wings, is eroded, has physical drop, etc. Note existence/type of inlet apron or protection.

Outlet: One or two word entry where necessary. Identify whether outlet has physical drop, falls over a barrier, has pool, etc. Note existence/type of any outlet apron or protection.

<u>IV. Other</u>
Photos: Digital photographs or video recommended.

Sketch: Sketch 'plan view' and unusual conditions on back of form or additional sheet.

Other observations: Include other considerations not specifically requested on form. Include anything considered appropriate - wildlife observations, plant community composition, severe erosion, pollution, etc.

Need further review: Is there need to gather additional or more complete information about site? Use your judgment to decide if conditions/resources warrant.

Maine Department of Transportation
Design Manual and Best Management Practices
Culverts for Fish Passage

Introduction

This manual is intended for the design of new and replacement culverts, as well as culvert rehabilitations, that will not block passage of identified fish species at specified design flows. Engineers will find these design guidelines useful in the implementation of Maine Department of Transportation (MDOT) fish passage policy as documented in the companion volume to this work (MDOT, 2002a). The manual is intended for use by MDOT engineers and designers as well as other engineers designing stream crossings in a fisheries environment. At this stage in the development of fish passage methodologies in Maine, stream crossings design for fish passage should be performed by or under the direct supervision of an experienced hydraulic engineer working with a fisheries biologist.

This manual is limited to culverts and does not address dedicated fishway passage structures. Furthermore, while it is recognized that culverts are usually the most desirable road crossing for small and medium sized streams from an engineering standpoint, from a fish passage perspective culverts are in fact less desirable than bridges and bottomless arches on footings. The final determination of the suitability of a culvert for fish passage rests with the fisheries biologist.

Culvert Barriers to Fish Passage

There are five common conditions at culverts that can create barriers to fish movement:

- excess drop at culvert outlet
- high velocity within culvert barrel
- inadequate depth within culvert barrel
- turbulence within culvert barrel
- debris accumulation at culvert inlet

Barriers are created by several conditions. Culverts are usually uniform and sized to pass peak design flows, e.g., the 50-year flood Q_{50}. They do not have the roughness and variability of natural stream channels and therefore do not dissipate kinetic energy effectively. Thus, velocities tend to be higher in a culvert than in the stream. This effect is amplified by the fact that existing culverts are often narrow, with a concomitant constriction of flow at the inlet. This may have the effect of increasing velocity in the pipe, creating turbulence at the inlet, and creating velocity-induced scour holes at the outlet. Outlet scour may induce a significant drop at the outlet. The last barrier condition, debris accumulation, is due to inadequate maintenance.

New and replacement stream crossings can be designed to avoid the first four, hydraulics related, barrier conditions. The last condition, even in a well-designed culvert, depends on good maintenance attuned to the specific fish passage requirements of a culvert. Fish passage can be difficult to restore in rehabilitated and retrofit culverts. Mitigating design elements in addition to the basic culvert lining are usually needed in order to establish passage under specified conditions.

General Steps in Design for Culvert Fish Passage

The following steps are generally followed when addressing fish passage through culverts.

1) identification of valuable habitat for specific species and need for passage by fisheries biologists in MDOT, resource agencies, and regulatory agencies
2) determination of calendar periods when passage must be provided
3) estimation of design flows during passage periods
4) culvert design
   a) new pipe: size pipe according to natural stream bankfull cross-section; check for extreme flow capacity and passage performance by hydraulic analysis
   b) rehabilitated pipe: hydraulic analysis to check performance of proposed rehabilitation; design mitigation measures (e.g., weirs, baffles, outlet notch ramps) if fish passage is inadequate

Design Approaches

Two basic design approaches are available. For new and replacement culverts, the preferred approach is to match culvert dimensions to natural bankfull stream channel hydraulic geometry, subject to standard MDOT culvert design practices. The assumption is that by matching hydraulic geometry in the range of critical fish passage flows, fish passage is assured. This approach is simple and minimizes the hydraulic and hydrologic analysis necessary.

For culvert rehabilitation (e.g., by slip or invert lining), the hydraulic approach is necessary. In this case, hydraulic analysis is employed to calculate water velocities and depths under design flows. Analysis is also employed to design mitigation measures needed to achieve velocities and depths that will pass fish. While the hydraulic approach is not required for designing new and replacement culverts, the hydraulic performance of such pipes should be checked for standard design floods (e.g., Q_{50}) as well as fish passage flows.

Hydrology and Design Flow Determination

New and replacement culverts must be designed to pass the 50-year flow event (or "flood") in accordance with MDOT Drainage Policy. Rehabilitated culverts should be evaluated for their ability to pass the 50-year flood, though the reduction in cross-sectional area and effects of fish passage mitigation measures may reduce the pipe capacity. Extreme flows should be estimated according to the methods used by MDOT in highway and bridge design.

In addition to the traditional peak flow design standard, culverts in selected fisheries should permit fish passage during a range of low flows. Two potential hydraulic problems are addressed in designing for fish passage. Water depth in the culvert may be inadequate to permit movement. This condition usually occurs in the lower range of low flows, hereafter called "low low flows". At somewhat higher low flows, or the "high low flows", the velocity in the culvert may be too high for fish to swim against in an upstream direction.

These potential barriers to passage establish two design objectives. These criteria are species-dependent and are summarized in the MDOT Fish Passage Policy. Occasionally, resource and regulatory agencies may directly specify a minimum depth and/or maximum velocity to be achieved. The two objectives relate to depth and velocity. Depending on the species present, not all cases will require both standards to be met:

1) maintain adequate in-culvert water depth for identified species during low flow conditions to allow passage;
2) during periods of upstream movement, flow velocity should not exceed species swimming capacity

These design standards are species- and season-dependent. The depth and flow velocity should be determined by hydraulic analysis and checked against species-dependent criteria. In the case of proposed rehabilitation, failure to meet standards will require mitigation measures or possibly a replacement pipe.

The following assumptions are implicit in an acceptable design:

1) adequate depth at low low flow automatically satisfies the velocity criterion
2) adequate velocity at high low flow automatically satisfies the depth criterion

These assumptions should be checked as part of the design process.

The design flows may be determined by

1) site inspection and measurement during periods of fish migration
2) estimation by USGS regression equations for monthly average flow (Parker, 1978)

3) calculation from specified or known depths in existing culvert known to pass fish

When these methods are not applicable, $Q_{1.1}$ as extrapolated from methods in Hodgkins (1999) may be used; contact MDOT Environment Office/Hydrology Section in this case.

New and Replacement Culverts – Hydraulic Geometry Matching

Designing new and replacement culverts for fish passage is much simpler than retrofitting existing pipes. The following guidelines should be followed:

1) Employ corrugated elliptical pipe arches with the largest feasible corrugations whenever possible
2) For nominal diameter (or rise) D < 1200 mm (48 in), embed pipe invert 150 mm (6 in) in stream bed; D > 1200 mm, embed pipe invert 300 mm (12 in); allow embedded pipe to fill with natural substrate
3) Embedded pipe cross-section should approximate natural bankfull width
4) Place pipe with zero slope, or as nearly flat as possible
5) Pipe should pass the 50-year flood, accounting for the capacity lost to embedding
6) Hydraulic analysis is needed to size the pipe for the peak flow and to check (but not design for) hydraulic performance during fish passage flows; irregular cross-section flow area (due to embedding and elliptical section) should be accounted for whenever possible.
7) In the event that culvert and stream geometry cannot be matched, a complete hydraulic analysis for passage conditions should be performed.

This approach works best on streams of gentle slope. Steeply sloped streams will likely require mitigation (e.g., weirs or baffles). Figure 1 shows an embedded circular pipe along with equations in Table 1 for calculating basic geometric quantities.

Figure 1: Embedded Circular Pipe

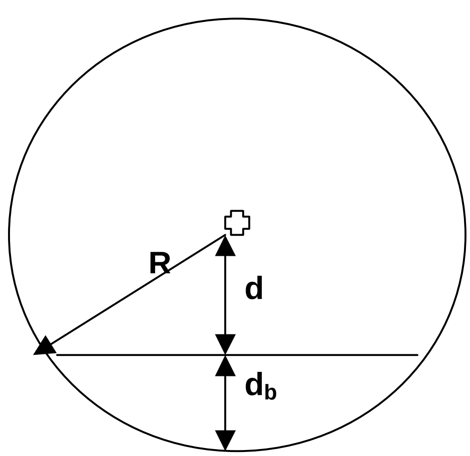


Table 1: Equations for Embedded Circular Pipe Geometry

Embedded Area	$A_b = R^2\cos^{-1}[(R-d_b)/R] - (R-d_b)\{2Rd_b-d_b^2\}^{0.5}$
Open Area	$A_o = \pi R^2 - A_b$
Embedded Perimeter	$P_b = 2R\cos^{-1}[(R-d_b)/R]$
Open Perimeter	$P_o = 2\pi R - P_b$
Distance from bed to center	$d = R - d_b$

These equations can be used to approximate elliptical pipes, with pipe rise substituted for diameter. More exact results can be calculated with the following equation:

$$A = b\,(\text{pipe rise})^a$$

The coefficients a and b are given in Table 2. Note that two sets of coefficients are given, for corner radii of 457 mm (18 in) and 787 mm (31 in). These coefficients were developed by regression analysis from the exact tabulated areas in Tables 3a and 3b, respectively. The tables can be used in place of the equations.

Table 2: Function Coefficients for Open Area in Embedded Elliptical Pipe

Corner Radius		**Depth of Embedment**			
		0 mm	150 mm (6 in)	225 mm (9 in)	300 mm (12 in)
457 mm	a	2.246	2.316	2.371	2.428
	b	0.995	0.893	0.823	0.752
787 mm	a	2.260	2.291	2.320	2.351
	b	0.859	0.807	0.766	0.721
18 in	a	2.246	2.316	2.371	2.428
	b	0.743	0.613	0.530	0.453
31 in	a	2.260	2.291	2.320	2.351
	b	0.631	0.571	0.524	0.475
Equation: open area $A = b \times (\text{pipe rise})^a$, in (m, m^2) and (ft, ft^2)					

Table 3a
OPEN AREA IN EMBEDDED ELLIPTICAL PIPE (metric)

Corner Radius	Span (m)	Rise (m)	Open Area (m^2) Depth of Embedding (mm) 0 mm	150 mm	225 mm	300 mm
Corner Radius = 457 mm	1.855	1.397	2.048	1.854	1.733	1.602
	1.931	1.448	2.231	2.061	1.936	1.800
	2.058	1.499	2.433	2.275	2.143	2.002
	2.134	1.550	2.630	2.450	2.313	2.165
	2.210	1.601	2.838	2.638	2.493	2.338
	2.337	1.651	3.062	2.876	2.727	2.565
	2.414	1.702	3.275	3.068	2.911	2.743
	2.490	1.753	3.504	3.272	3.105	2.929
	2.617	1.804	3.743	3.533	3.371	3.185
	2.693	1.855	3.985	3.750	3.573	3.383
	2.846	1.905	4.255	4.041	3.866	3.672
	2.896	1.956	4.503	4.278	4.080	3.878
	2.973	2.007	4.767	4.501	4.303	4.092
	3.125	2.058	5.049	4.817	4.623	4.409
	3.252	2.109	5.343	5.123	4.923	4.740
	3.328	2.160	5.634	5.395	5.196	4.972
	3.481	2.210	5.950	5.727	5.541	5.321
	3.532	2.261	6.235	5.994	5.785	5.561
	3.608	2.312	6.544	6.283	6.064	5.820
	3.760	2.363	6.887	6.643	6.441	6.203
	3.811	2.414	7.194	6.932	6.706	6.461
	3.862	2.464	7.522	7.236	7.026	6.729
	3.913	2.541	7.945	7.628	7.374	7.100
	4.090	2.566	8.221	7.937	7.700	7.426
	4.243	2.617	8.600	8.335	8.115	7.854
	4.294	2.668	8.946	8.662	8.417	8.147
	4.345	2.718	9.302	8.994	7.823	8.444
	4.522	2.769	9.720	9.434	9.197	8.943
	4.675	2.820	10.122	9.855	9.631	9.367

Corner Radius	Span (m)	Rise (m)	Open Area (m^2) Depth of Embedding (mm) 0 mm	150 mm	225 mm	300 mm
	4.726	2.871	10.497	10.212	9.974	9.693
	4.776	2.922	10.884	10.579	10.325	9.810
	4.827	2.998	11.399	11.071	10.798	10.478
	5.005	3.023	11.729	11.425	11.171	10.872
	5.056	3.074	12.135	11.809	11.538	11.217
Corner Radius = 787 mm	4.040	2.846	9.080	8.833	8.615	8.391
	4.116	2.896	9.461	9.197	8.977	8.728
	4.268	2.947	9.880	9.629	9.420	9.174
	4.319	2.998	10.247	9.981	9.756	9.503
	4.395	3.049	10.646	10.360	10.123	9.854
	4.548	3.100	11.087	10.819	10.595	10.331
	4.675	3.150	11.511	11.254	11.039	10.787
	4.751	3.201	11.934	11.663	11.436	11.170
	4.827	3.252	12.370	12.073	11.826	11.535
	4.954	3.303	12.809	12.534	12.306	12.038
	5.030	3.354	13.255	12.966	12.724	12.442
	5.183	3.404	13.739	13.447	13.205	12.919
	5.234	3.455	14.017	13.724	13.481	13.193
	5.310	3.506	14.645	14.337	14.079	13.777
	5.462	3.557	15.153	14.859	14.615	14.326
	5.513	3.608	15.608	15.300	15.042	14.738
	5.666	3.659	16.131	15.835	15.589	15.298
	5.716	3.709	16.605	16.294	16.036	15.730
	5.869	3.760	17.147	16.847	16.598	16.305
	5.945	3.811	17.662	17.347	17.087	16.779
	5.996	3.862	18.160	17.830	17.559	17.237
	6.072	3.913	18.693	18.348	18.059	17.719
	6.225	3.963	19.257	18.928	18.654	18.331
	6.275	4.014	19.772	19.427	19.139	18.799

Table 3b
OPEN AREA IN EMBEDDED ELLIPTICAL PIPE (British)

	Span (ft)	Rise (ft)	Open Area (ft²)			
			Depth of Embedding (in)			
			0 in	6 in	9 in	12 in
Corner Radius = 18 in	6.08	4.58	22.03	19.95	18.64	17.24
	6.33	4.75	24.00	22.17	20.83	19.37
	6.75	4.92	26.17	24.47	23.06	21.54
	7.00	5.08	28.29	26.36	24.88	23.29
	7.25	5.25	30.53	28.38	26.82	25.15
	7.67	5.42	32.94	30.94	29.34	27.60
	7.92	5.58	35.23	33.01	31.32	29.51
	8.17	5.75	37.70	35.20	33.41	31.51
	8.58	5.92	40.27	38.01	36.27	34.27
	8.83	6.08	42.87	40.34	38.44	36.40
	9.33	6.25	45.78	43.48	41.59	39.50
	9.50	6.42	48.44	46.02	43.89	41.72
	9.75	6.58	51.29	48.42	46.29	44.02
	10.25	6.75	54.32	51.82	49.74	47.43
	10.67	6.92	57.48	55.11	52.96	51.00
	10.92	7.08	60.61	58.04	55.90	53.49
	11.42	7.25	64.01	61.61	59.61	57.25
	11.58	7.42	67.08	64.49	62.24	59.83
	11.83	7.58	70.40	67.59	65.24	62.61
	12.33	7.75	74.09	71.47	69.30	66.73
	12.50	7.92	77.40	74.58	72.15	69.51
	12.67	8.08	80.93	77.85	75.59	72.39
	12.83	8.33	85.48	82.07	79.33	76.38
	13.42	8.42	88.44	85.39	82.84	79.89
	13.92	8.58	92.52	89.67	87.30	84.50
	14.08	8.75	96.25	93.19	90.55	87.65
	14.25	8.92	100.07	96.76	84.16	90.84
	14.83	9.08	104.57	101.50	98.95	96.21
	15.33	9.25	108.90	106.02	103.61	100.77

	Span (m)	Rise (m)	Open Area (ft²)			
			Depth of Embedding (in)			
			0 in	6 in	9 in	12 in
	15.50	9.42	112.93	109.86	107.30	104.28
	15.67	9.58	117.09	113.81	111.08	105.54
	15.83	9.83	122.64	119.11	116.17	112.73
	16.42	9.92	126.19	122.91	120.18	116.96
	16.58	10.08	130.55	127.05	124.13	120.68
Corner Radius = 31 in	13.25	9.33	97.69	95.03	92.68	90.27
	13.50	9.50	101.79	98.94	96.58	93.90
	14.00	9.67	106.29	103.59	101.34	98.70
	14.17	9.83	110.24	107.38	104.96	102.24
	14.42	10.00	114.53	111.46	108.91	106.01
	14.92	10.17	119.28	116.39	113.98	111.14
	15.33	10.33	123.84	121.07	118.76	116.05
	15.58	10.50	128.39	125.47	123.03	120.17
	15.83	10.67	133.08	129.89	127.23	124.10
	16.25	10.83	137.80	134.85	132.39	129.51
	16.50	11.00	142.60	139.49	136.89	133.86
	17.00	11.17	147.81	144.67	142.06	138.99
	17.17	11.33	150.80	147.65	145.03	141.94
	17.42	11.50	157.56	154.24	151.47	148.22
	17.92	11.67	163.02	159.86	157.23	154.12
	18.08	11.83	167.92	164.60	161.83	158.56
	18.58	12.00	173.54	170.36	167.71	164.58
	18.75	12.17	178.64	175.30	172.52	169.23
	19.25	12.33	184.47	181.25	178.57	175.42
	19.50	12.50	190.01	186.63	183.83	180.52
	19.67	12.67	195.37	191.82	188.91	185.44
	19.92	12.83	201.11	197.39	194.29	190.63
	20.42	13.00	207.17	203.64	200.69	197.21
	20.58	13.17	212.72	209.00	205.91	202.25

Rehabilitated Culverts - Mitigation Measures

Existing culverts can be rehabilitated by slip lining and by invert lining. However, linings reduce both cross-sectional flow area and surface roughness, with a possible net effect of decreasing flow depth and/or increasing flow velocity. The simplest approach to maintaining fish passage is to install a new pipe designed for consistency with the prevailing stream hydraulic geometry. Budgetary and other constraints may argue against replacement. If the culvert is on an identified fishery, then design measures may need to be taken in order to insure fish passage under specified conditions.

When selecting a passage mitigation measure, the first step is to determine if the lined culvert will be a barrier to passage. This requires hydrologic and hydraulic analysis by a trained hydraulic engineer. Target design flows are chosen according to guidelines presented here and in the companion Maine DOT Fish Passage Policy volume (MDOT, 2002a). Then the lined pipe is evaluated for acceptable depth and velocity, according to the target species. In general, if downstream control on shallow water depths does not previously exist, then mitigation measures are likely necessary.

When a pipe is lined, the invert is raised by approximately 125 mm (5 in) due to the concrete or plastic lining. This may create a slightly hanging invert or a drop too great for fish to pass over. This effect is separate from the hydraulic aspects of depth and velocity. A sluice channel in the outlet can be employed to eliminate this drop.

Culvert hydraulic analysis can be performed with software such as HY8 or equivalent proprietary software for the design flows and incorporating tailwater conditions as determined by site inspection. If flow depth is too shallow or velocity too high, then the following two general measures suggest themselves for increasing depth:

- Sluice channels in bottom of culvert (culvert end treatments for fish passage)
- tailwater control structures (weirs) installed downstream
- baffles installed in the culvert

When the lining-induced drop is not too great, a simple notched sluice channel in the bottom of the culvert may provide adequate water depth. Hanging culverts can also be corrected by tailwater control, provided the drop is not too extreme.

Weirs are preferred over baffles because they are easier to build and maintain. Weirs also require long-term maintenance, but they provide easier access. Therefore, baffles should only be resorted to when weirs are inappropriate, usually because of site conditions.

Culvert End Treatments for Fish Passage – Notched Outlets

Placement of culvert lining raises the outlet invert. If the induced jump is modest, it can be mitigated by building a ramped notch (sluice channel) into the bottom of the culvert. The ramped notch is like a sluiceway built into the bottom of the pipe. The notch invert is at stream grade, providing a continuous stream/culvert bottom elevation. The sluiceway returns to the prevailing invert elevation some distance into the culvert.

Typical details for two different culvert end treatment options are show in Figures 2 (Option 1; notch terminates at end of pipe) and 3 (Option 2; notch extends beyond pipe). Treatment 1 is intended for modest drops while treatment 2 is for deeper drops. Treatment 1 includes a riprap apron to provide a smooth transition from stream bed to the pipe edge. The notched channel should be sized to run full at low flow.

This treatment is used primarily to eliminate hanging inverts. End treatments by themselves will not correct excessive velocities or inadequate depths farther up the culvert. Hydraulic analysis should be performed to check that:

1) adequate flow depth is achieved in the upper portion of the pipe
2) velocity standard is not exceeded in pipe and notch channel

Regardless of the specific end treatment, care should be exercised in the use of rock riprap. Rock absorbs solar and thermal energy and therefore functions as a heat sink. Excessive rock can lead to warming of the stream water, possibly creating a thermal barrier to fish passage.

Figure 2: End Treatment to Eliminate Drop, Option 1

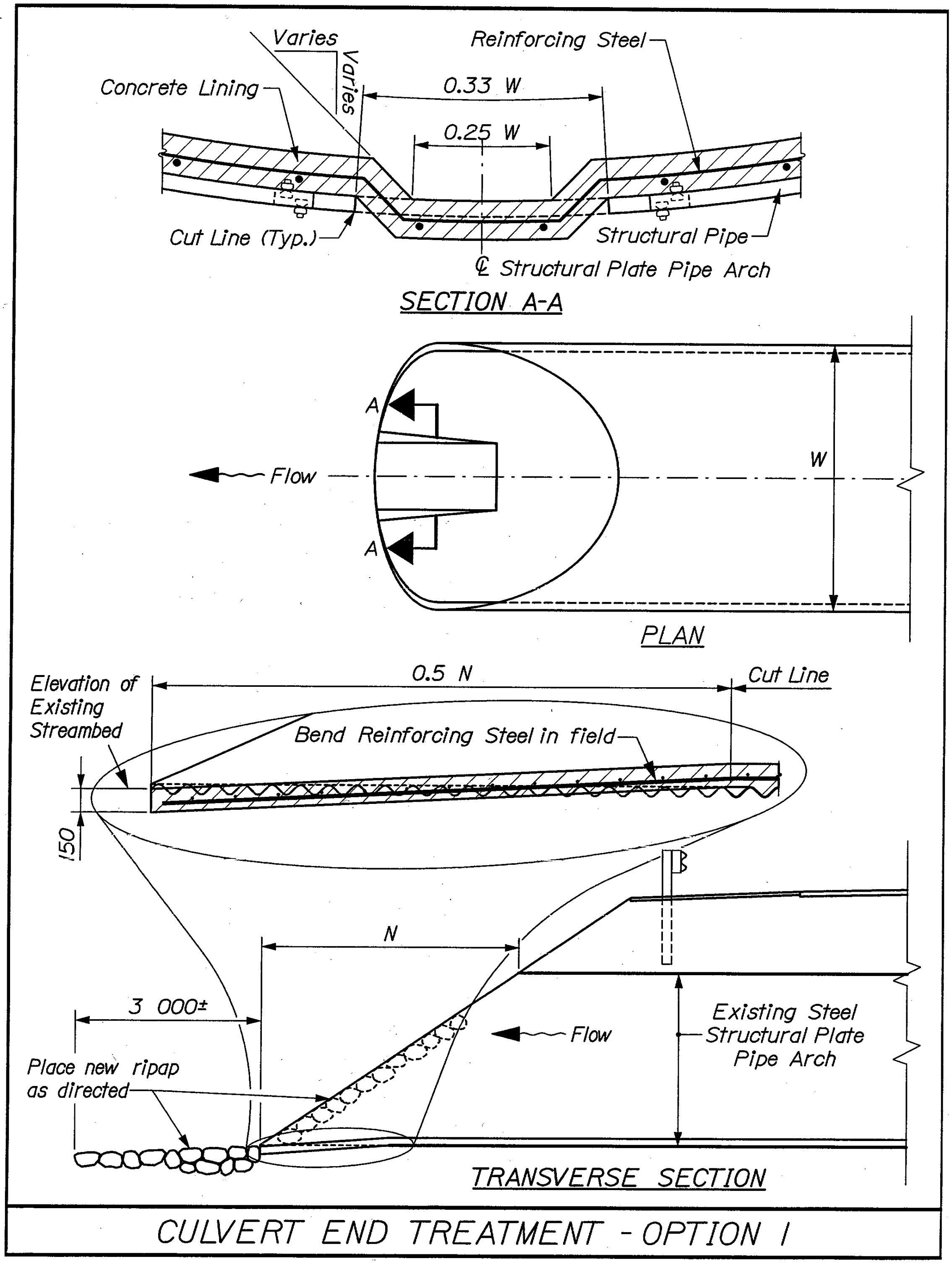
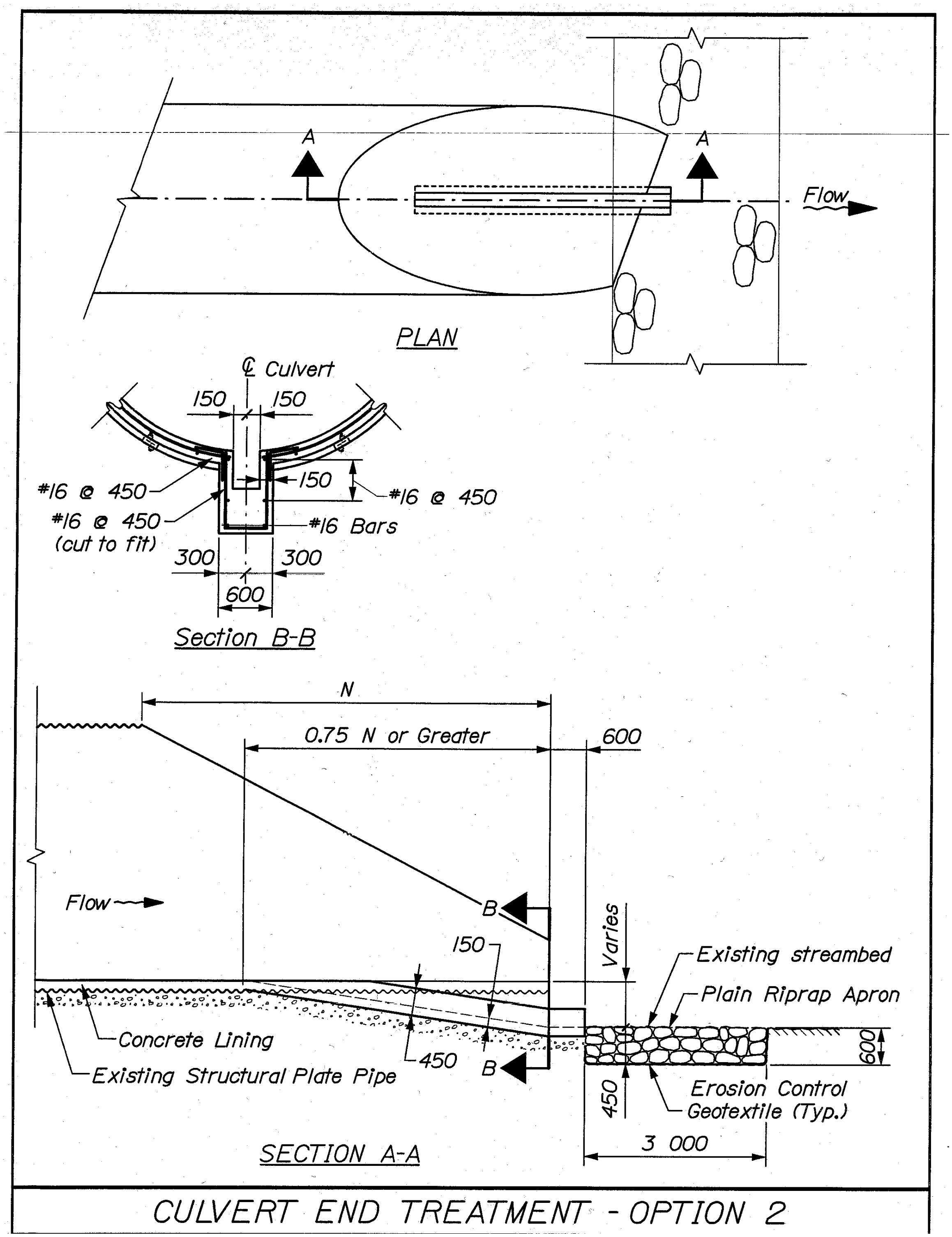


Figure 3: End Treatment to Eliminate Drop, Option 2



Grade Control Structures (Weirs)

Weirs are used to establish grade control, i.e., to back water up into the culvert to the needed depth. The required tailwater elevation is determined using HY8 or similar approved culvert hydraulics procedure. The minimum depth required for passage must be obtained up to and including the inlet. Placement of weirs in turn creates drops in water elevation downstream of the culvert and creates the possibility that the solution to fish passage (the weir) in turn becomes a barrier. The drop at any particular weir should ordinarily be limited to 150 mm (6 in) in order to allow for passage over the weir. Thus, several weirs in series may be needed to create the needed tailwater elevation at low low flow conditions. The distance between weirs should be about 150% of the stream width in smaller streams, with a target minimum spacing of 5 m (16.5 ft), up to 10 m (33 ft) in larger streams. For reasons of cost and downstream impact, the number of structures should be kept to a minimum.

Weirs should be constructed of natural materials when possible, e.g., logs on a stone foundation in smaller streams; weirs on larger streams may be constructed of rock. The simplest weir extends straight across the stream; alternative plan forms are V-shaped, pointing up or down stream. The log ends should be anchored to stone or block on the stream bank. The banks in the vicinity of the log ends should be riprapped to prevent scour and channel migration at higher flow. The foundation stones should be sized to withstand the 100-year flood and wrapped in geofabric so that they stand as a unit, thereby achieving additional stability. The wrap also seals the log structure and forces more of the water over the weir or through the spillway, rather than between the logs. The logs can be stacked vertically or angled downstream; angling creates quiescent water beneath the crest where fish can rest. The weir should be square-notched, according to the idea that fish will be attracted to and pass through the water spilling through the notch. The notch should be sized to flow full at low flow. Details for a log grade control structure (i.e., weir) is shown in Figures 4 and 5.

Weirs, while preferable to baffles in many respects, present their own problems. Common to baffles, weirs add additional maintenance responsibilities to DOT. Weirs can create access and right-of-way issues, especially when a series of weirs is needed to obtain the necessary tailwater. With typical inter-weir spacing of 3 m – 5 m (10 ft – 16.5 ft), several weirs will probably extend beyond existing right-of-way. If additional drainage easement cannot be obtained, in-culvert weirs might be considered.

As noted generally for culvert end treatments, the use of rock riprap should be controlled so as not to induce heating of water.

Figure 4: Log Drop Control Structure

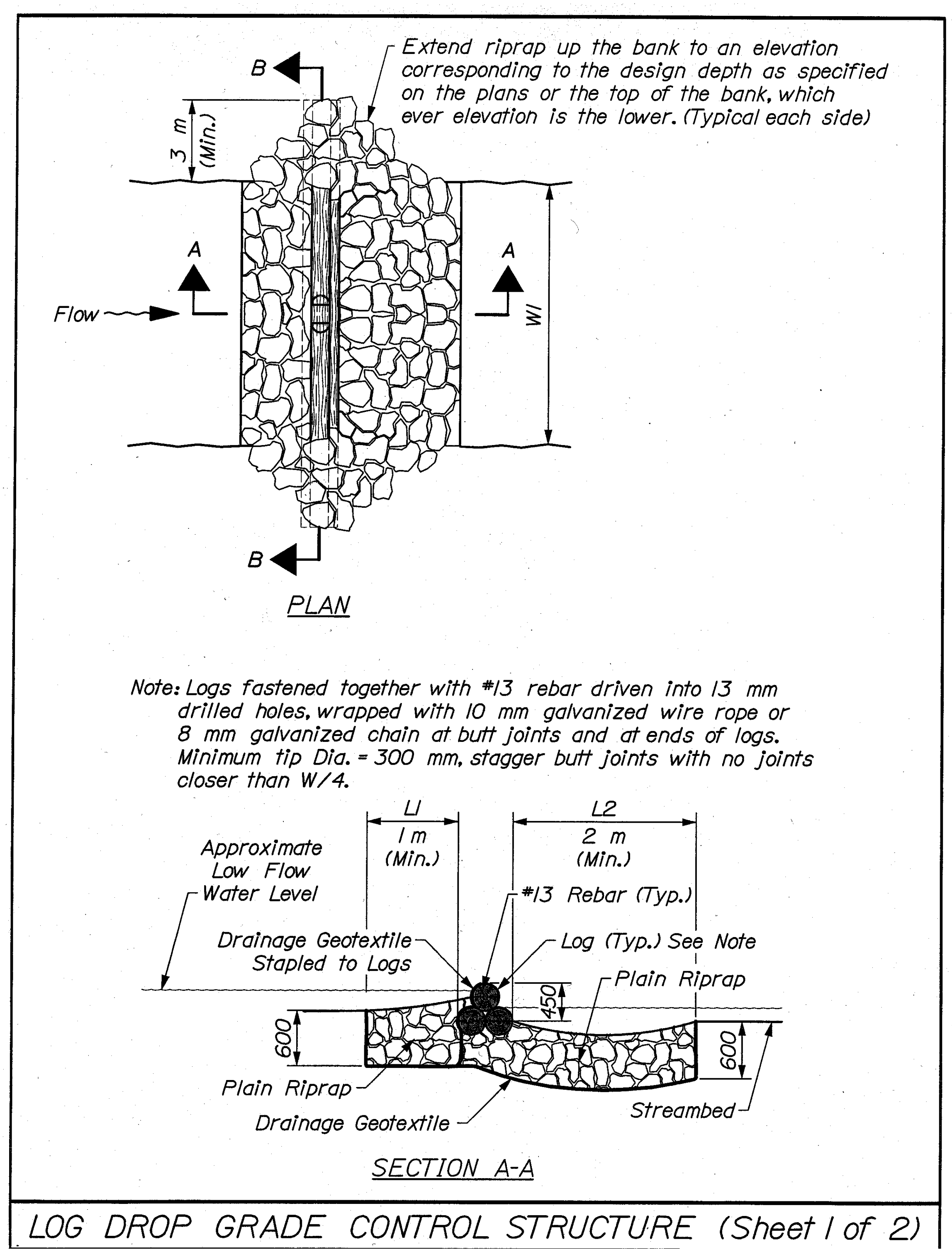
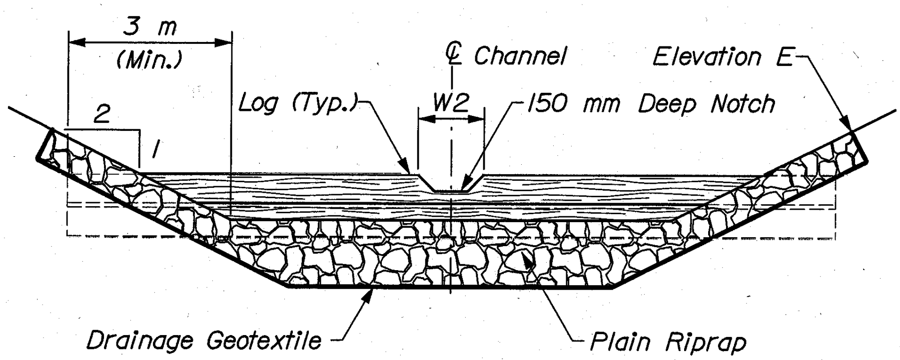


Figure 5: Log Drop Control Structure (cont.)

NOTE: 1.) Channel Width (W1) as specified on the Plans.
2.) Notch Width (W2) as specified on the Plans.
3.) Upstream Length (L1) as specified on the Plans.
4.) Downstream Length (L2) as specified on the Plans.
5.) Top of Riprap Elevation (E) as specified on the Plans.



SECTION B-B

LOG DROP GRADE CONTROL STRUCTURE (Sheet 2 of 2)

Baffles

Baffles function as large discrete roughness elements in the pipe bottom. Baffles raise water levels, slow velocities, and establish resting pools between baffles. The between-baffle spaces may also fill with sediment, suggesting the possibility of establishing a natural stream bottom in the pipe. Properly designed and constructed, baffles have been demonstrated to pass fish (Nash Creek culvert in R.L. Currie, 1997). As inter-baffle spacing gets large, the baffles effectively function as weirs (as opposed to roughness elements) and should be thought of as such.

In-pipe baffles present several problems that often make them less attractive than other measures.

- performance may deteriorate over time if between-baffle spaces fill with sediment. The roughness effect of protruding baffles may diminish, with some possible compensation provided by roughness of natural bottom materials.
- access problems during construction and maintenance limit their use to larger pipes (e.g., $d \geq 1800$ mm = 6 ft)
- the baffles may trap debris or may be destroyed during high flows
- they detract from the hydraulic capacity of the pipe

In general, the use of sluiceway end treatments and weirs should be investigated before baffles are employed.

Katapodis (1992) summarizes the hydraulic performance of several baffle configurations. When the baffle extends across the pipe bottom width, it is called a "weir baffle". Other configurations use notched ("slotted") baffles and baffle sections arranged in an offset fashion ("offset" baffles). The methods of Katapodis can be used to estimate depth and velocity under design flow conditions. These configurations are shown in schematic in Figure 6. Typical details for weir baffles and offset baffles are shown in Figures 7 and 8 respectively. The offset baffle arrangement is preferred over other arrangements. In general, minimum baffle height should be in the order of 300 mm (1 ft) to achieve desired results. Figure 9 shows a single end-treatment weir baffle.

Reduction of velocity throughout the length of pipe may require frequently spaced baffles, resulting in a large number of baffles at large cost. An alternative design approach uses baffles to establish resting pools for fish within the pipe, relying on their higher burst speed to carry them from baffle to baffle. The baffles effectively function as weirs, accounting for the term "weir and pool", also "baffled and sill" structures. Offset baffles also create resting pools, even though the baffles are not continuous across the culvert. This permits larger spacing between baffles (weirs) and average flow velocity in the pipe higher than the nominal sustainable swimming speed. This is an important option to consider when other approaches do not yield cost-effective or feasible designs.

The methods of Katapodis (1992) should be used to calculate velocities and inter-baffle spacing. These methods are summarized below.

Figure 6: Schematic of Baffle Arrangements

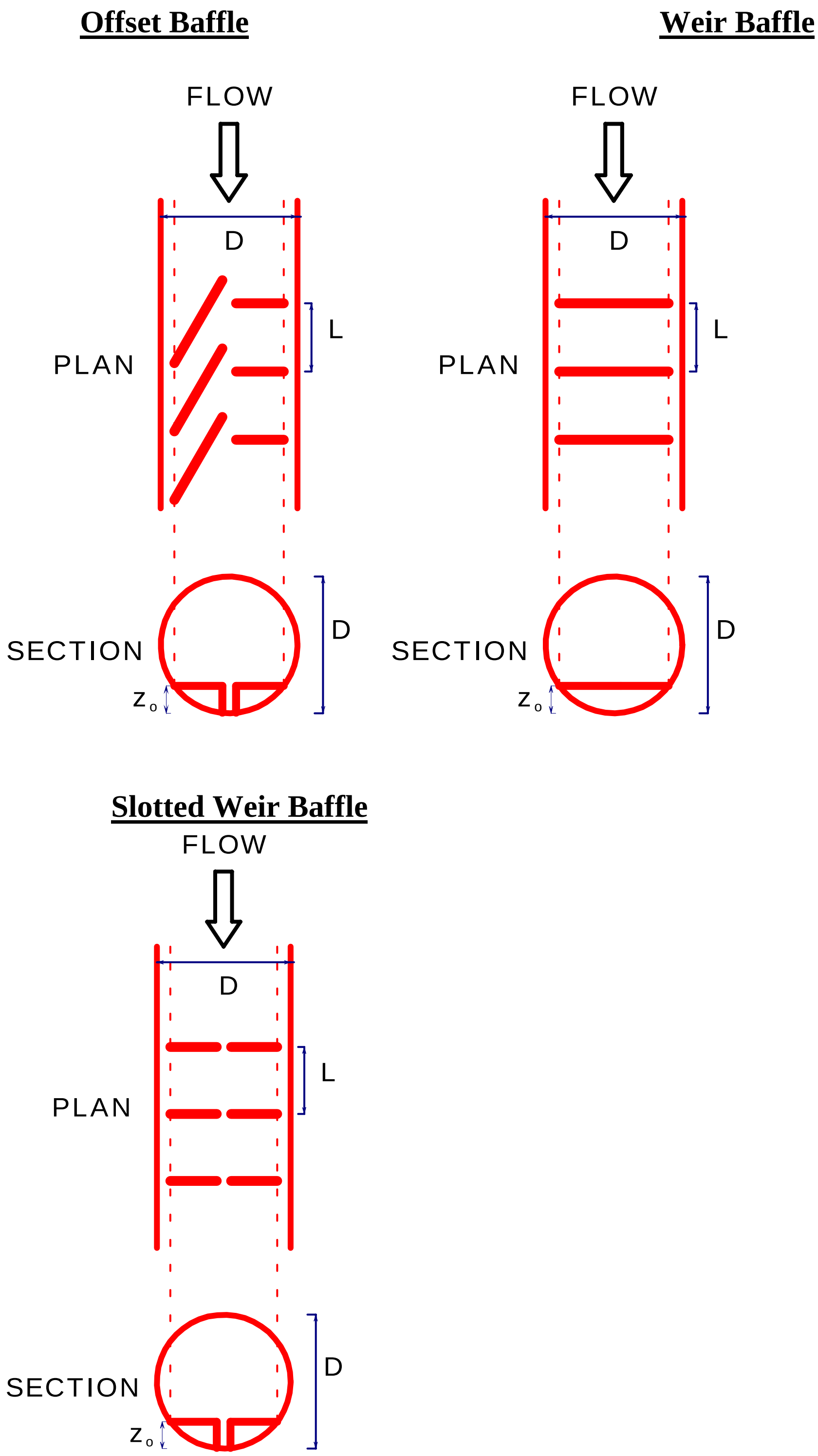


Figure 7: Concrete Baffle Detail

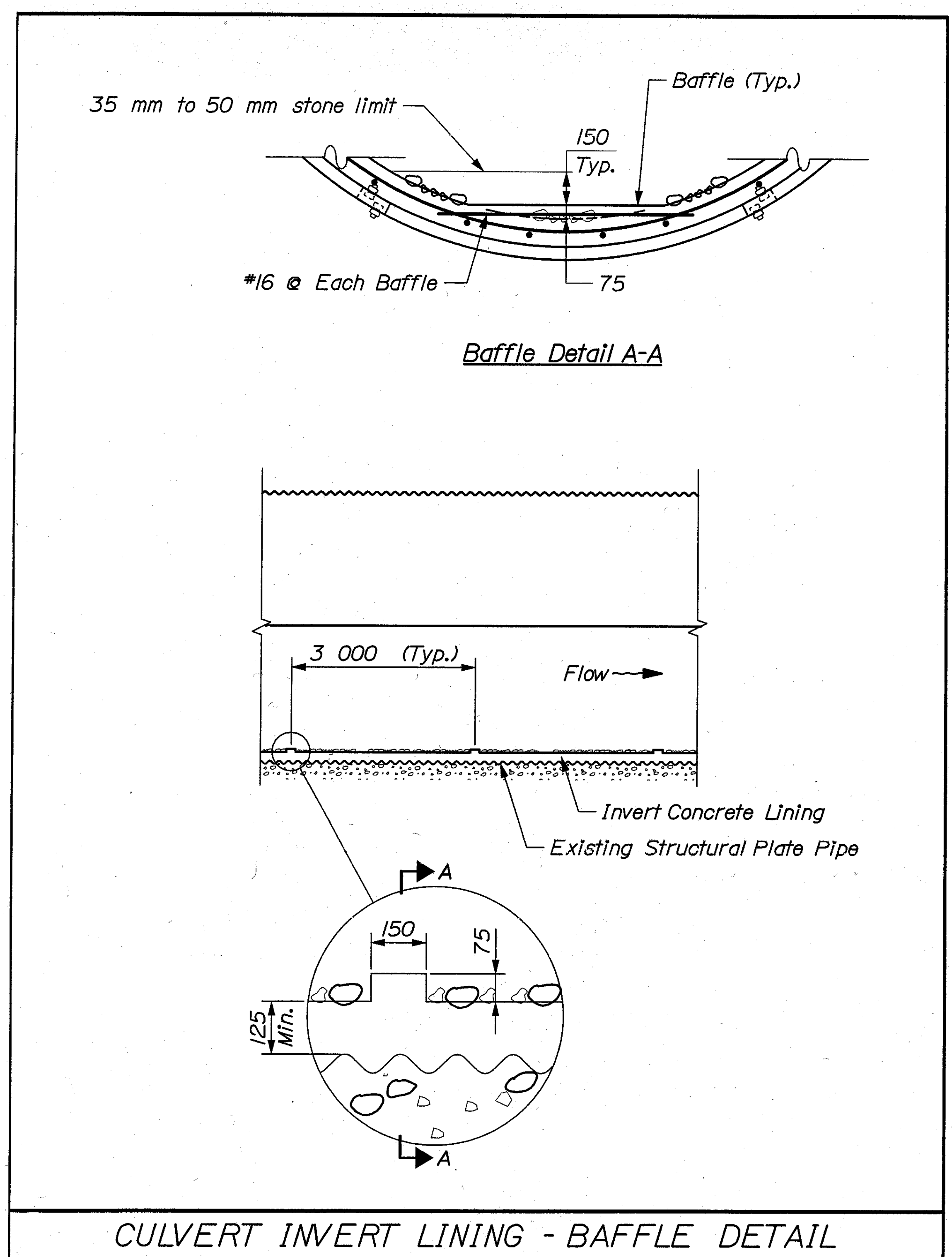
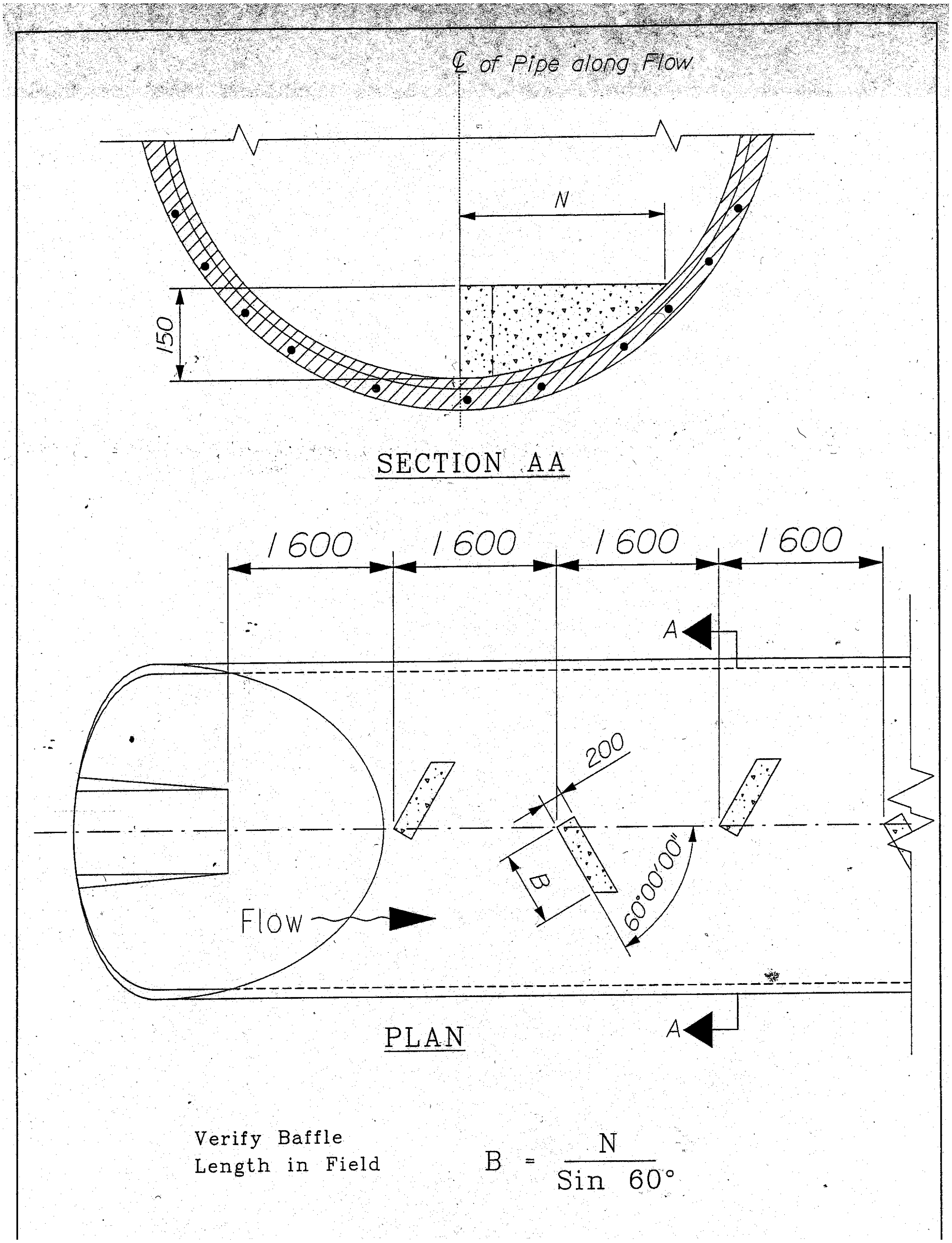
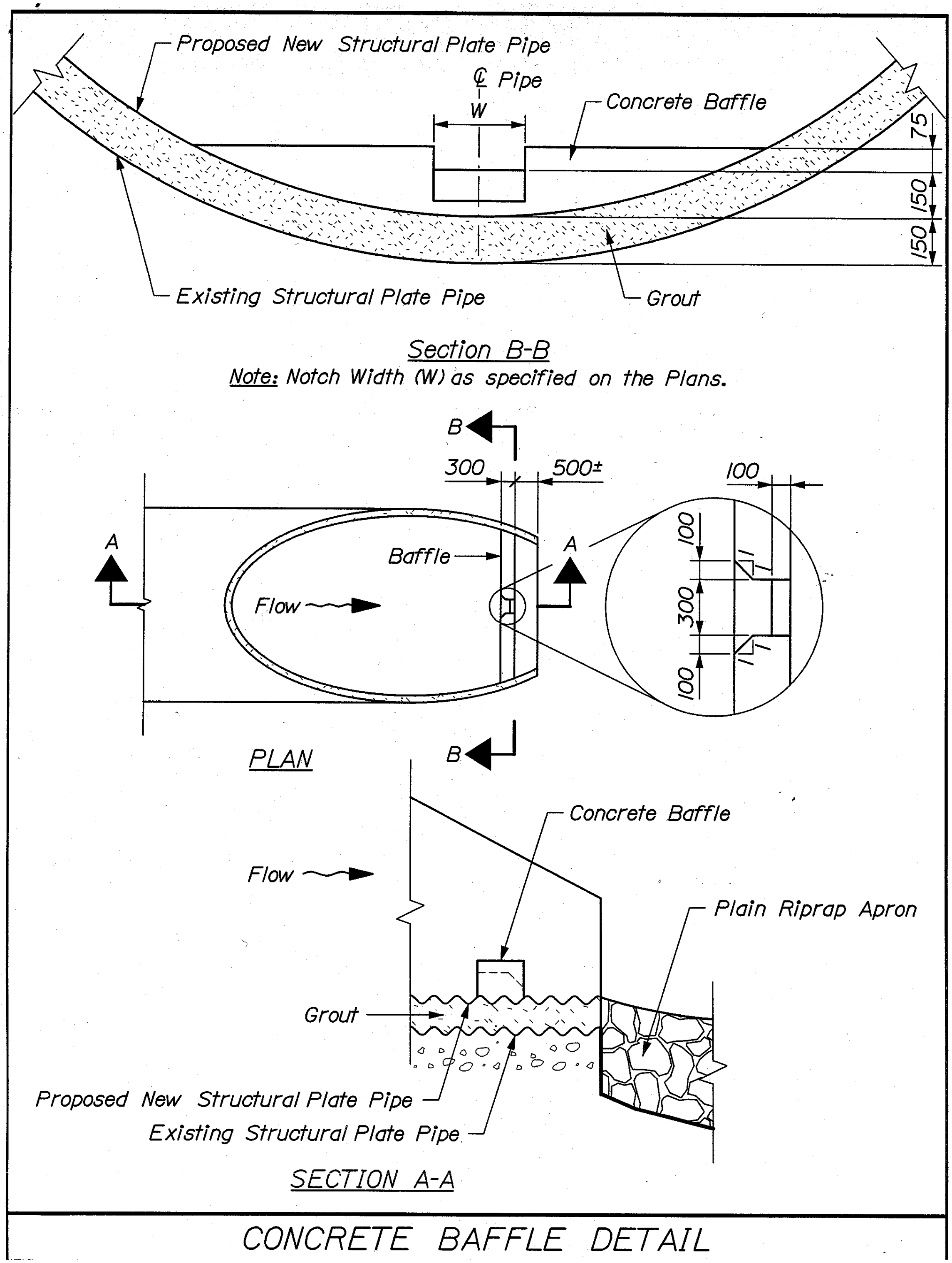


Figure 8: Offset Baffle Detail



$$B = \frac{N}{\text{Sin } 60°}$$

Figure 9: End Weir Baffle



Hydraulic Analysis

Standard Methods
Hydraulic analysis of culverts should be performed according to methods in HDS-5 (FHWA, 1985), either manually or by computer. New and replacement pipes should be designed by standard methods, subject to the additional requirements of matching channel geometry and embedding. The embedded pipe capacity should be checked against the 50-year flood.

For culvert rehabilitations, the existing pipe should be analyzed to see if it meets passage criteria. The proposed lining should be evaluated for the 50-year flood and any passage criteria, without any mitigation measures (baffles, weirs, etc).

Standard methods such as HDS-5 are suitable for evaluating the effect of tailwater as created by downstream weirs. However, they are not appropriate for evaluating pipe baffles. Baffles should be evaluated using the methods of Katapodis.

Baffles
Katapodis gives flow equations for several baffle configurations. The simplest, and most likely to be used, are the offset, weir, and slotted weir arrangements. Flow equations are of the general form

$$Q_* = Q/\{gSD^5\}^{1/2} = \alpha(y_o/D)^\beta$$

Where Q_* = dimensionless discharge
g = acceleration due to gravity
S = channel slope
D = pipe diameter
α, β = empirical coefficients
Q = actual discharge
y_o = actual flow depth

The coefficients α and β depend on the baffle arrangement; (y_o/D) is a relative depth.

Velocity profiles follow the relationship

$$U_* = u_m/\{gSD\}^{1/2} = \alpha(y_o/D) + \beta$$

$$u/u_m = \alpha(y/z_o)\beta$$

where U_* = dimensionless velocity
u_m = maximum velocity in culvert
z_o = baffle height

The α and β coefficients are different for the discharge and velocity equations. Coefficients for different arrangements are summarized in Tables 4, 5, and 6 for offset, weir, and slotted weir baffles, respectively. For a given design discharge and assumed design, these equations can be used to estimate depth of flow y_o and maximum velocity u_m. The design is revised until acceptable results are obtained. If a weir-and-pool approach is employed, these results can be used in conjunction with the species burst speed to determine adequate inter-weir spacing.

Figure 10: Offset Weir Schematic

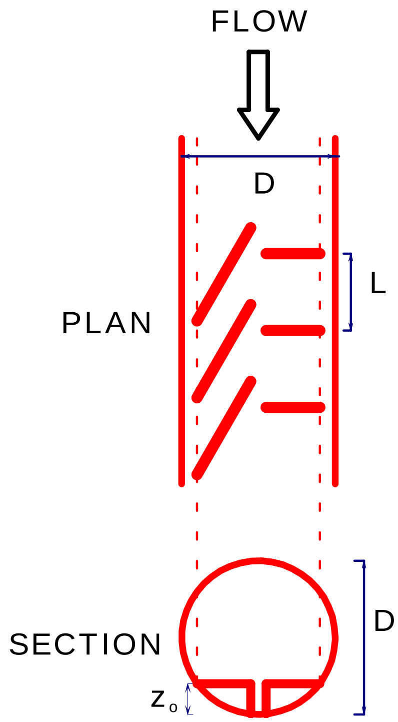


Table 4: Offset Weir Coefficients

Design	Dimensions		Discharge Equation Q*			Velocity Equation U*		
	L	z_o	y_o/D	α	β	y_o/D	α	β
D-1	0.67D	0.1D	0.029-0.565	12	2.60	0.09-0.37	12.8	0
D-2	0.67D	0.2D	0.146-0.462	11.14	3.63	0.22-0.42	5.60	0
D-3	0.33D	0.1D	0.076-0.469	9.38	2.62	0.14-0.34	10.2	0
D-4	1.01D	0.10D	0.055-0.448	9.48	2.57			

Figure 11: Weir Baffle Schematic

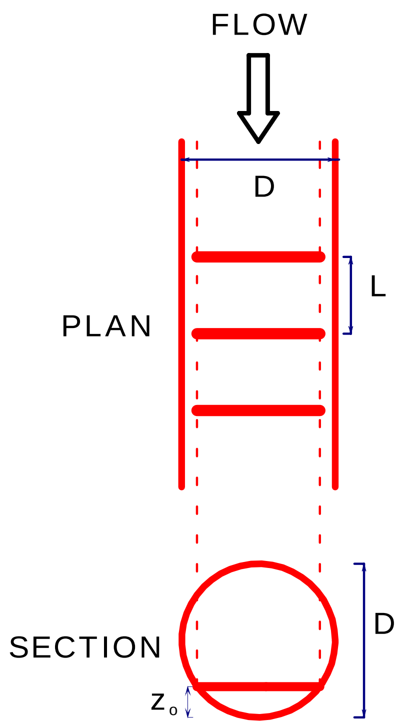


Table 5: Weir Baffle Coefficients

Design	Dimensions		Discharge Equation Q_*			Velocity Equation U_*		
	L	z_o	y_o/D	α	β	y_o/D	α	β
W-1	0.6D	0.15D	0.17-0.25	549	5.78	0.23-0.61	8.6	0
			0.25-0.81	5.39	2.43			
W-2	1.2D	0.15D	0.18-0.35	35.3	4.14	0.29-0.61	8.6	0
			0.35-0.9	6.6	2.62			
W-3	0.6D	0.1D	.01-0.2	443196	8.63	0.24-0.53	10.9	0
			0.2-0.9	8.62	2.53			
W-4	1.2D	0.1D	0.2-0.9	9	2.36			

Figure 12: Slotted Weir Schematic

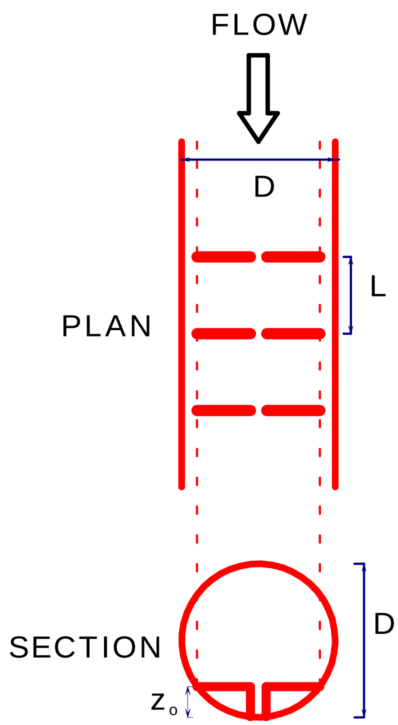


Table 6: Slotted Weir Baffle Coefficients

Design	Dimensions		Discharge Equation Q_*			Velocity Equation U_*		
	L	z_o	y_o/D	α	β	y_o/D	α	β
SW-1	0.6D	0.15D	0.12-0.85	9.2	3.0	0.15-0.79	9.2	0
SW-2	0.3D	0.15D	0.15-0.84	9.2	3.0	0.18-0.78	9.2	0
SW-3	1.2D	0.15D	0.14-0.76	12.4	3.1	0.13-0.72	10.9	0
SW-4	2.4D	0.15D	0.16-0.68	13.8	3.1	0.14-0.67	12.7	0
SW-5	0.6D	0.15D	0.10-0.73	13.7	2.9	0.12-0.68	11.4	0
SW-6	1.2D	0.15D	0.10-0.67	14.9	3.0	0.13-0.68	12.4	0

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